Optical Engineering

OpticalEngineering.SPIEDigitalLibrary.org

Rotation of an optically trapped vaterite microsphere measured using rotational Doppler effect

Xinlin Chen
Guangzong Xiao
Wei Xiong
Kaiyong Yang
Hui Luo
Baoli Yao

SPIE.

Xinlin Chen, Guangzong Xiao, Wei Xiong, Kaiyong Yang, Hui Luo, Baoli Yao, "Rotation of an optically trapped vaterite microsphere measured using rotational Doppler effect," *Opt. Eng.* **57**(3), 036103 (2018), doi: 10.1117/1.OE.57.3.036103.

Rotation of an optically trapped vaterite microsphere measured using rotational Doppler effect

Xinlin Chen,[a] Guangzong Xiao,[a,b,*] Wei Xiong,[a] Kaiyong Yang,[a] Hui Luo,[a,*] and Baoli Yao[b]
[a]National University of Defense Technology, College of Optoelectronic Science and Engineering, Changsha, China
[b]Chinese Academy of Sciences, State Key Laboratory of Transient Optics and Photonic, Xian, China

Abstract. The angular velocity of a vaterite microsphere spinning in the optical trap is measured using rotational Doppler effect. The perfectly spherical vaterite microspheres are synthesized via coprecipitation in the presence of silk fibroin nanospheres. When trapped by a circularly polarized beam, the vaterite microsphere is uniformly rotated in the trap center. The probe beams containing two Laguerre–Gaussian beams of opposite topological charge $l = \pm 7$, $l = \pm 8$, and $l = \pm 9$ are illuminated on the spinning vaterite. By analyzing the backscattered light, a frequency shift is observed scaling with the rotation rate of the vaterite microsphere. The multiplicative enhancement of the frequency shift proportion to the topological charge has greatly improved the measurement precision. The reliability and practicability of this approach are verified through varying the topological charge of the probe beam and the trapping laser power. In consideration of the excellent measurement precision of the rotation frequency, this technique might be generally applicable in studying the torsional properties of micro-objects. [DOI: 10.1117/1.OE.57.3.036103]

Keywords: laser Doppler velocimetry; optical tweezers or optical manipulation; backscattering; optical sensing and sensors.

Paper 171976 received Dec. 11, 2017; accepted for publication Feb. 14, 2018; published online Mar. 7, 2018.

1 Introduction

The linear Doppler effect is a familiar concept, in which the relative motion between source and receiver causes a frequency shift. This frequency shift scales with the linear velocity and is generally applicable in monitoring the translational motion.[1,2] Since first proposed by Yeh and Cummins[3] in 1964, just a few years after the invention of the laser, the laser linear Doppler technique has become an efficient tool for velocity measurement of surface,[4] fluid,[5] and atmospheric turbulence.[6] In recent years, a rotational analog to linear Doppler effect, namely rotational Doppler effect, has drawn great attention. In this effect, a laser beam carrying spin or orbital angular momentum (OAM) is illuminated on a roughness object rotating along the beam axis, and a Doppler frequency shift will be generated on the scattered light.[7] The rotational Doppler effect was first realized by Garetz and Arnold[8] through the circularly polarized light that carries spin angular momentum (SAM). In their research, the circularly polarized light that passed through a half-wave retardation plate rotating with angular velocity ω suffered a frequency shift of 2ω. In 1992, Allen et al.[9] recognized the laser beams carrying OAM, which is many times greater than the SAM. As a conclusion, the rotational Doppler frequency shift for OAM can be many times greater than that of SAM, which was soon theoretically verified by Nienhuis[10] in 1996. Since then, this technique has been widely used to probe the angle velocity of spinning objects.[11–15] In 2014, the rotational Doppler effect was first combined with optical traps to measure the rotation rate of a microscopic calcite.[16,17] This has immensely expanded the application of the rotational Doppler effect in microscopic domain. However, the irregular calcite crystals might lead to an unstable rotation speed.[18] This has greatly disturbed the accurate measurement. In addition, the topological charge of the helically phase beam still remains to be enhanced to improve the measurement precision.

In this paper, the rotation frequency of optical trapped vaterite microsphere was measured by rotational Doppler effect. The vaterite microsphere was perfectly spherical so that it could be uniformly rotated by circularly polarized light. By referring to the previous works,[16,17] we chose two Laguerre–Gaussian (LG) beams of opposite topological charge $l = \pm 7$, $l = \pm 8$, and $l = \pm 9$ as probe beams. The multiplicative enhancement of the frequency shift has greatly improved the measurement precision. This technique might be applicable in studying the torsional properties of micro-objects.

2 Fundamentals

The linear Doppler effect is applicable to beams of all types. As shown in Fig. 1(a), when an arbitrary beam is emitted on the translating object with a relative velocity v, the scattered beam will suffer a frequency shift. The Doppler frequency shift is given as

$$\Delta f = \frac{f_0 v \sin \alpha}{c}, \tag{1}$$

where f_0 is the unshifted frequency, α is the incident angle, and c is the speed of light.

As shown in Fig. 1(b), there will be an analogous frequency shift for a helically phase beam emitted on an object rotating around the beam axis. This phenomenon is called rotational Doppler effect. The rotational Doppler frequency shift

*Address all correspondence to: Guangzong Xiao, E-mail: xiaoguangzong@nudt.edu.cn; Hui Luo, E-mail: luohui.luo@163.com

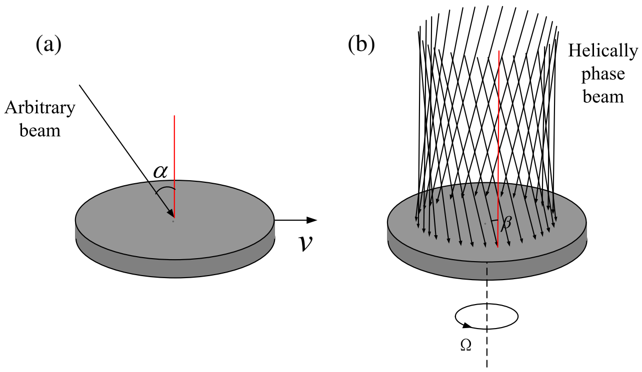

Fig. 1 (a) Linear Doppler effect and (b) rotational Doppler effect.

$$\Delta f' = f_0 v' \sin\beta/c = f_0 2\pi r\Omega \sin\beta/c, \tag{2}$$

where Ω is the rotation frequency, v' is the tangential velocity, r is the radius from the beam axis, and β is the skew angle between the Poynting vector and the beam axis, which can be given as

$$\beta = \sin^{-1}(cl/2\pi f_0 r), \tag{3}$$

where l denotes the topological charge of the helically phase beam. If the incident beam contains two helically phased beams of opposite values of l, the frequency shift will be in opposite direction, which will give an intensity modulation of frequency[13]

$$f_{\text{mod}} = 2\Delta f' = 2f_0 v \sin\beta/c = 2l\Omega. \tag{4}$$

Hence, the rotation frequency of the object could be measured by detecting beat frequency f_{mod}, and the measurement precision is $2l$ times enhanced.

3 Experimental Setup

The optical layout for the experiment is shown in Fig. 2. A circularly polarized beam was provided by a single-mode laser diode (Thorlabs, CLD1015, 975 nm) to trap and rotate the vaterite microsphere. The trapping beam was focused into the sample through an oil immersion objective (Nikon, E Plan ×100, NA = 1.25). A 532-nm solid-state laser was used to provide the probe beam, which is then shaped by a spatial light modulator (SLM, HOLOEYE, PLUTO-NIR-011). The backscattered light containing the rotational Doppler modulated signal was monitored by a photodetector (PD, Thorlabs, PDB210A). A single emitter white-light LED (Thorlabs, LEDWE-10) was used to illuminate the sample. The light coming from the LED passed through the dichroic mirrors and was ultimately imaged on a CCD camera (Thorlabs, DCU224).

Measuring with rotational Doppler effect requires the use of two helically phased beams of opposite values of l. In the experiment, we displayed the phase profile image as shown in Fig. 3(a) to the SLM. When the horizontal polarized probe beam was emitted on the SLM, its phase contrast would be adjusted according to the phase profile image. As a result, the reflected beam would contain two LG beams of $l = \pm 8$. Its far-field intensity profile is presented in Fig. 3(b). The interference between two LG beams produced a "petal"-shaped intensity pattern with the number of petals given by $2l$.

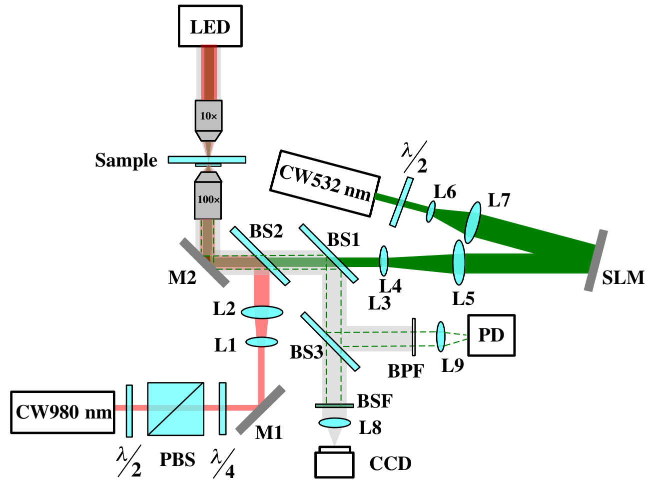

Fig. 2 The experimental setup used for the rotational Doppler effect. Labels denote the continuous wave (CW), half-wave plate ($\lambda/2$), polarizing beam splitter (PBS), quarter-wave plate (l/4), mirror (M), lenses (L), beam splitter (BS), SLM, bandpass filter (BPF), bandstop filter (BSF), and photodiodes (PD)

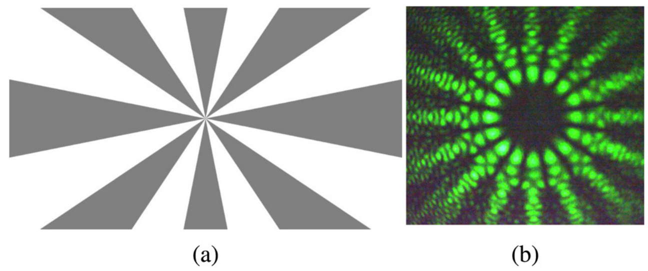

Fig. 3 (a) Phase profile of LG ±8 modes and (b) corresponding far-field intensity profile.

Rather than relying on natural calcite crystals, which are irregular in shape, we choose vaterite microspheres to be the rotated sample. Silk fibroin nanospheres are used as a modifier to grow perfectly spherical birefringent particles of vaterite.[19] In the experiment, the aqueous solution of silk fibroin nanospheres (4 wt. %, 15 g) was injected into the $CaCl_2$ solution (0.54 mol/L, 5 mL). Then an aqueous

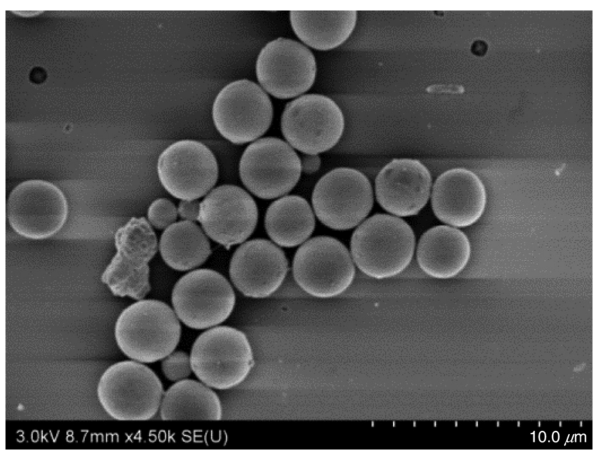

Fig. 4 SEM image of the silk fibroin regulated vaterite microspheres.

solution of NH_4HCO_3 (1.08 mol/L, 5 mL) was added into the blend solution under vigorous stirring at 700 rpm. The obtained suspension was centrifuged and eventually getting the silk fibroin regulated vaterite microspheres. Figure 4 shows the scanning electron microscopy (SEM) image of the vaterite microspheres. The obtained vaterite microspheres are much better sphericity and more uniform than the natural calcite crystals. As a result, they could be rotated at a constant speed when trapped by circularly polarized beam,[20,21] which contributes to the rotational Doppler effect. In addition, the crystal structure of the vaterite microsphere has enough rotational symmetry to enable the smooth rotation. The diameters of the vaterite microspheres are $\sim 3\ \mu$m.

4 Results and Discussion

According to Eq. (4), for the probe beam containing two LG beams of opposite values of l, their scattering light has opposite frequency shifts, which result in an intensity modulation. The beat frequency is calculated to be $2l\Omega$. We set up the experiment optical system as in Fig. 2. When trapped by the circularly polarized beam, the vaterite microsphere began to rotate in the trap center at a constant frequency. The trapping beam power was 100 mW. The probe beam at 532 nm was shaped by the SLM and contained two LG beams of $l = \pm 7$, $l = \pm 8$, and $l = \pm 9$, successively. The laser power is the same for all three measurements. In each case, the time-varying signal obtained by the PD was Fourier transformed to produce a power spectrum. The results are shown in Figs. 5(a)–5(c), respectively. The frequency resolution is 0.1 Hz. The beat frequencies for the three cases are measured to be (221.9 ± 1.7) Hz, (252.5 ± 0.8) Hz, and (284.1 ± 0.2) Hz. The measurement precision depends on the full width at half maximum (FWHM) of the spectral peak. According to Eq. (4), these values correspond to the rotation frequencies of (15.85 ± 0.12) Hz, (15.78 ± 0.05) Hz, and (15.78 ± 0.01) Hz, respectively. Precision of the measurement is enhanced by improving the values of l. The calculated rotation frequencies in each case have excellent agreement, which verifies the reliability and practicability of the proposed approach.

The shoulder peaks in Fig. 5 are mainly caused by the poor signal-to-noise ratio (SNR). As the surface of the vaterite microsphere is not rough enough, the power of the backscattered light may be very weak relative to the noise. As a result, the beat frequency peak would be relatively low, and then the shoulder peaks revealed. The SNR varies with the topological charge l. When $l = \pm 8$, the SNR is relatively small in order that the beat frequency peak is relatively low. The noise is mainly introduced by the Brownian motion of the vaterite microsphere, the background light, and the PD noise. It is unrelated to the topological charge l. The signal depends on the power of the backscattered light, which is determined by the surface roughness of the incident point. The ring width of the LG light changes with l, so does the incident point. Hence, as the topological charge l changes, the power of the backscattered light changes and so does the SNR of the detection.

To further test the relationship predicted in Eq. (4), we varied the rotation frequency of the vaterite microsphere by changing the trapping beam power. The vaterite microsphere was illuminated with a LG light of $l = \pm 8$. The measured beat frequency and the calculated rotation frequency versus the trapping laser are exhibited in Fig. 6. The error bars denote the measurement precision. The red solid line represents the linear fitting result. The data show that the beat frequency increases linearly with the trapping beam power. As a result, the rotation frequency calculated according to Eq. (4) increases linearly with the trapping beam power.

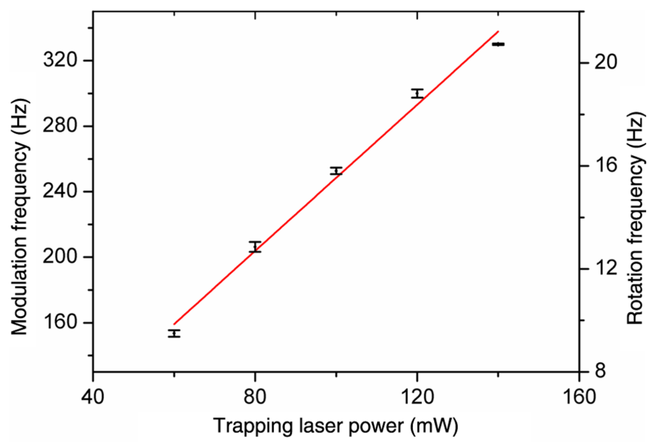

Fig. 6 Beat frequency and calculated rotation frequency versus the trapping laser power for probe beam of $l = \pm 8$. The error bars denote the FWHMs of the spectral peak. The red solid line represents the linear fitting result.

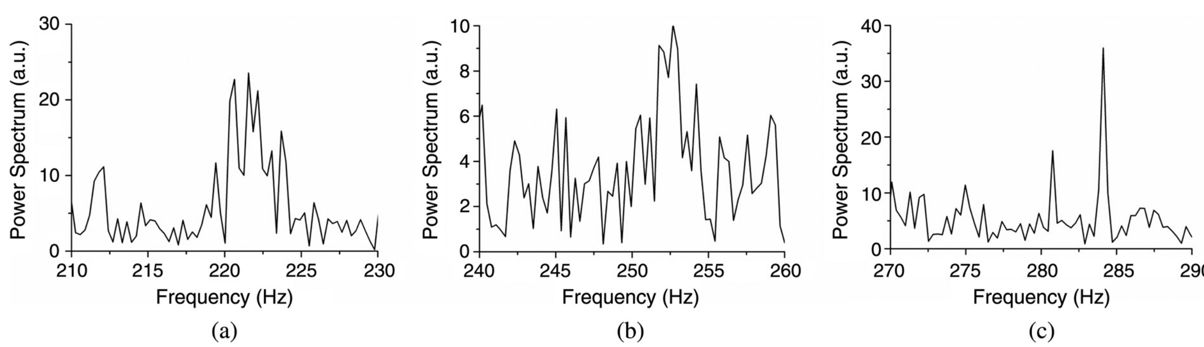

Fig. 5 Power spectra for probe beams consisting two LG lights of (a) $l = \pm 7$, (b) $l = \pm 8$, and (c) $l = \pm 9$. The corresponding beat frequencies are 221.9 ± 1.7 Hz, 252.5 ± 0.8 Hz, and 284.1 ± 0.2 Hz (measured as FWHM).

5 Conclusion

It is demonstrated that the rotation frequency of the optical trapped vaterite microsphere could be measured using rotational Doppler effect. A perfectly spherical vaterite microsphere modified by silk fibroin nanospheres was trapped by a circularly polarized beam and rotated at a constant speed. The probe beams containing two LG beams of $l = \pm 7$, $l = \pm 8$, and $l = \pm 9$ were illuminated on the vaterite microsphere, respectively. The backscattered light was monitored by a PD to detect the rotation frequency. The rotation frequencies in the three cases were measured to be (15.85 ± 0.12) Hz, (15.78 ± 0.05) Hz, and (15.78 ± 0.01) Hz. The experimental results have got excellent consistency, and the precision of the measurement is greatly enhanced. In addition, the rotation frequency of the trapped vaterite microsphere was varied by adjusting the trapping beam power. The measured beat frequency and the corresponding rotation frequency both increased linearly with the trapping beam power, which further demonstrated the reliability of the rotational Doppler effect.

In summary, we have introduced the rotational Doppler effect to directly measure the rotation frequency of the optical trapped micro-object. This approach allows accurately detecting the torques exerted on single biomolecules and is applicable in studying their torsional properties. This will contribute to a greater understanding of the biological systems. Furthermore, this approach might also be efficient to monitor the viscosity of the surrounding fluid.

Acknowledgments

The project was supported by the Hunan Provincial Natural Science Foundation of China (No. 2017JJ3363) and the Open Research Fund (No. SKLST201507) of State Key Laboratory of Transient Optics and Photonics, Chinese Academy of Sciences. The authors would like to acknowledge Professor Qiang Lv from Soochow University and Yansheng Liang from State Key Laboratory of Transient Optics and Photonic, Chinese Academy of Sciences for their kind help.

References

1. A. J. Oberholster and P. S. Heyns, "Eulerian laser Doppler vibrometry: online blade damage identification on a multi-blade test rotor," *Mech. Syst. Signal Process.* **25**(1), 344–359 (2011).
2. B. J. Halkon and S. J. Rothberg, "Rotor vibration measurements using laser Doppler vibrometry: essential post-processing for resolution of radial and pitch/yaw vibrations," *J. Vib. Acoust.* **128**(1), 8–20 (2006).
3. Y. Yeh and H. Z. Cummins, "Localized fluid flow measurements with an He-Ne laser spectrometer," *Appl. Phys. Lett.* **4**(10) 176–178 (1964).
4. Z. Jian and L. Xingwu, "Research on laser Doppler velocimeter for vehicle self-contained inertial navigation system," *Opt. Laser Technol.* **42**(3), 477–483 (2010).
5. C. Riva, B. Ross, and G. B. Benedek, "Laser Doppler measurements of blood flow in capillary tubes and retinal arteries," *Invest. Ophthalmol.* **11**(11), 936–944 (1972).
6. I. Smalikho, F. Köpp, and S. Rahm, "Measurement of atmospheric turbulence by 2-μm Doppler lidar," *J. Atmos. Ocean. Technol.* **22**(11), 1733–1747 (2005).
7. B. Garetz, "Angular Doppler effect," *J. Opt. Soc. Am.* **71**(5), 609–611 (1981).
8. B. Garetz and S. Arnold, "Variable frequency-shifting of circularly polarized laser radiation via a rotating half-wave retardation plate," *Opt. Commun.* **31**(1), 1–3 (1979).
9. L. Allen et al., "Orbital angular-momentum of light and the transformation of Laguerre–Gaussian laser modes," *Phys. Rev. A* **45**(11), 8185–8189 (1992).
10. G. Nienhuis, "Doppler effect induced by rotating lenses," *Opt. Commun.* **132**(1–2), 8–14 (1996).
11. R. Simon, H. J. Kimble, and E. C. G. Sudarshan, "Evolving geometric phase and its dynamical manifestation as a frequency shift: an optical experiment," *Phys. Rev. Lett.* **61**(1), 19–22 (1988).
12. I. Bialynicki-Birula and Z. Bialynicka-Birula, "Rotational frequency shift," *Phys. Rev. Lett.* **78**(13), 2539–2542 (1997).
13. M. P. J. Lavery et al., "Detection of a spinning object using lights orbital angular momentum," *Science* **341**(6145), 537–540 (2013).
14. A. Ryabtsev et al., "Fluid flow vorticity measurement using laser beams with orbital angular momentum," *Opt. Express*, **24**(11) 11762–11767 (2016).
15. O. Korech et al., "Observing molecular spinning via the rotational Doppler effect," *Nat. Photonics* **7**(9), 711–714 (2013).
16. D. B. Phillips et al., "Rotational Doppler velocimetry to probe the angle velocity of spinning micro-particle," *Phys. Rev A.* **90**(1), 011801 (2014).
17. D. B. Phillips et al., "Observation of the rotational Doppler effect from an optically trapped micro-particle," *Proc. SPIE* **9164**, 91640J (2014).
18. Yogesha, S. Bhattacharya, and S. Ananthamurthy, "Characterizing the rotation of non symmetric objects in an optical tweezer," *Opt. Commun.* **285**(10), 2530–2535 (2012).
19. L. Liu et al., "Biomineralization of stable and monodisperse vaterite microspheres using silk nanoparticles," *ACS Appl. Mater. Interfaces* **7**(3), 1735–1745 (2015).
20. J. Courtial et al., "Measurement of the rotational frequency shift imparted to a rotating light beam possessing orbital angular momentum," *Phys. Rev. Lett.* **80**(15), 3217–3219 (1998).
21. Y. Arita, M. Mazilu, and K. Dholakia, "Laser-induced rotation and cooling of a trapped microgyroscope in vacuum," *Nat. Commun.* **4**(1), 2374 (2013).

Xinlin Chen is a PhD candidate at the National University of Defense Technology. He received his BS and MS degrees in physics from the National University of Defense Technology in 2011 and 2013, respectively. He is the author of more than five journal papers. His current research interests include optical trap, optical inspection, and optoelectronic systems.

Guangzong Xiao received his PhD from National University of Defense Technology in 2011. Currently, he is a lecturer at National University of Defense Technology. His research focuses on the optical trap.

Wei Xiong is a PhD candidate at the National University of Defense Technology. He received his BS and MS degrees in physics from the National University of Defense Technology in 2012 and 2013, respectively. He is working on optical trap and optical inspection.

Kaiyong Yang received his PhD from National University of Defense Technology. Currently, he is a professor at National University of Defense Technology.

Hui Luo received his PhD from National University of Defense Technology in 1997. Currently, he is a professor at National University of Defense Technology.

Baoli Yao is a professor at Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences. He received his PhD at Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences in 1997.